



## Marked-Up Version of

## Substitute Specification Under 37 C.F.R. 1.125

# DISK DRIVE WITH METHOD AND APPARATUS FOR THE TEMPERATURE

## 5 COMPENSATION OF WRITE CURRENT AND WRITE CURRENT BOOST

### CROSS REFERENCE TO RELATED APPLICATIONS

This application claims pPriority is claimed from U.S. Patent Application Serial  
10 No. 60/257,133 filed December 20, 2000, entitled “~~TEMPERATURE COMPENSATION~~  
~~FOR WRITE CURRENT AND WRITE CURRENT BOOST~~”, the disclosure of which is  
incorporated herein by reference in its entirety.

## FIELD OF THE INVENTION

15           The present invention relates to adjusting the write current and write current boost  
in a hard-disk drive in response to changes in temperature.

~~In particular, the present invention relates to preventing pole tip protrusion and write induced instabilities as a result of elevated temperatures in combination with excessive amounts of write current and write current boost.~~

## 20 BACKGROUND OF THE INVENTION

DHard disk drives are used to store large amounts of digital data. Typically, the data is stored on magnetic storage disks in concentric tracks. The data tracks are usually divided into servo sectors that store servo information and data sectors that store user data. A read/write head reads data from and writes data Information is written to and

~~read from the a-disk by a transducer head. The transducer-head may includes a read element and head-separate from a write element that may be separate elements head, or the read and write heads may be integrated into a single integrated element read/write head. The transducer-head is mounted on an actuator arm assembly that capable of~~

5 ~~movesing the transducer-head radially over the disk. Accordingly, the movement of the actuator arm assembly allows the transducer-head to access different data-tracks on the disk. The disk is rotated by a spindle motor at a-high speed, allowing the transducer-head to access different data sectors within each track on the disk.~~

~~Disk drives include Various-parameters that of the performance of a hard-disk drive-are dependent, at least in part, on temperature. For example, the amount of write current supplied to the head required to sufficiently magnetize the storage-disk such that data is reliably encoded on the disk increases as the temperature of the disk drive decreases. The need for an-increased write current at reduced temperatures is the results from several of various-factors. For instance, the disk coercivity of the magnetic-storage disk, and thus the magnetic field strength of the field-required to encode a pattern of magnetization on the disk, increases as the temperature of the magnetic media of the storage-disk decreases. In addition, the flying height of the transducer-head over the surface of the magnetic-disk increases as the temperature decreases since and the air density of the air-inside the disk drive increases, and. A higher flying height generally~~

15 ~~requires a-larger write current is required to magnetize the disk due to the increased distance between the transducer-head and the surface of the magnetic-disk.~~

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~~At elevated temperatures, the amount of write current required to encode data on the magnetic-storage-disk decreases. In part, this is because the coercivity of the~~

magnetic storage media decreases as temperature increases. Therefore, a lesser magnetic field strength, and thus a lower write current, is required to encode data on the magnetic disk. In addition, the flying height of the transducer head at elevated temperatures is generally lower, because the air is less dense, placing the transducer head in closer proximity to the magnetic media.

Disk drives In order to provide a write current that is operative in most situations, the designers of hard disk drives have attempted to use ~~choose~~ a satisfactory write current amount that is satisfactory over a variety of anticipated operating temperatures, have been provided with Other methods for avoiding problems due to inappropriate write current amounts include screened in transducer heads to eliminate heads that those with a poor writer (i.e. write heads requiring large write amounts of current), and have operated under restricted in the operating temperature ranges of the disk drive.

However, as the data storage densities and data transfer rates of hard disk drives have increased, the ability of hard disk drives to tolerance ~~tolerance~~ for variations in written data has decreased. It is known in the art to vary the amount of write current or write current boost based on the zone on the disk in which the write is to occur. However, such variation is adapted to the different data frequencies used in different zones. Therefore, in order to ensure that data is written consistently, a need has emerged to vary the amount of write current used to encode data in response to temperature changes in temperature.

Disk drives have Attempts have been made to varied the write current amounts with temperature to maintain a desired track width since, because changes in disk the coercivity and/or flying height of the transducer head results in data tracks having varying track widths. However, this in conventional disk drives the amplitude of write

~~current boost has not been adjusted in response to temperature. In addition, conventional disk drives have neglected to consider other problems head instability and head deformation that may result from write current amounts that isare inappropriate for a given temperature.~~

5       ~~As an example, deformation of the transducer head may occur due to a combination of elevated ambient temperatures and high write currents and write current boosts. Such deformations may include pole tip protrusion, in which the transducer head protrudes from the surface of the slider. In such a condition, the transducer head is more likely to come into contact with the storage media, both because of the protruding~~  
10 ~~transducer head and because the flying height of the transducer head is lower at elevated temperatures, when pole tip protrusion is more likely to occur. Contact between the transducer head and the storage media can damage the storage media and the transducer head. In addition, such contact can result in positioning errors and increases in the data error rate of the hard disk drive. However, existing systems have generally not~~  
15 ~~considered pole tip protrusion in determining appropriate amounts of write current.~~

~~As a further example, Head instability arises from too high a write current and/or too high a write current and elevated temperature, thereby causing boost for the temperature of the transducer head can cause instabilities in the transducer head. Such instabilities can lead to a temporary or even a permanent inability of the transducer head~~  
20 ~~to reliably and accurately read and/or write data from the disk. In particular, the read element suffers from. In particular, an excessive write current and/or write current boost can cause write induced instability~~ies in the read head due to pinning ~~of of the magnetic domains and becomes in the read head, causing the read head to be insensitive to to the~~

magnetic fields on the disk associated with encoded data. Further, as areal densities have increased, transducer heads have become narrower, increasing their sensitivity to write induced instabilities.

Head deformation also arises from high write current and elevated temperature.

- 5 In particular, the write element suffers from pole tip protrusion and is more likely to contact with the disk. Head-disk contact can damage the head and the disk, misposition the head and cause data errors.

## SUMMARY OF THE INVENTION

- 10 In accordance with the present invention provides ,temperature compensation for write current in a disk drive and write current boost is provided. The write current not only provides an acceptable bit error rate for data written to and read from the disk, but also In particular, the present invention provides temperature compensation for write current and write current boost in order to prevent deformation of the transducer head and
- 15 to prevents write induced instability in the headies, thereby helping to ensure that data can be reliably stored and retrieved. Furthermore, the write current prevents excessive pole tip protrusion. As a result, the write current ensures that data is reliably stored and retrieved at a given temperature.

- In an embodiment, a method of compensating the write current for a temperature
- 20 of the disk drive includes measuring an ambient temperature of the disk drive, providing a first write current with acceptable bit error rate at the ambient temperature by adjusting an initial write current, and then providing a second write current with acceptable stability of the head at the ambient temperature by adjusting the first write current.

The method can include measuring the ambient temperature by measuring an internal temperature of the disk drive using a temperature sensor in the disk drive and performing a calculation using the internal temperature.

5 The method can also include providing the first write current by writing a test sequence to the disk using the head, reading the test sequence from the disk using the head, measuring a bit error rate of the read test sequence, comparing the measured bit error rate to a threshold, and changing the write current in response to the comparison.

The method can also include providing the second write current by reading servo information from the disk using the head, and changing the write current in response to  
10 an error in the read servo information.

The method can also include providing a third write current with acceptable pole tip protrusion of the head at the ambient temperature by adjusting the second write current. The third write current can be provided by reading servo information from the disk using the head, generating a position error signal in response to the read servo  
15 information, comparing the position error signal to a threshold, and changing the write current in response to the comparison.

~~In accordance with an embodiment of the present invention, a write current and a write current boost that provide the desired write characteristics are determined for a hard disk drive at a first temperature. In general, the write current and write current boost~~  
20 ~~should be chosen to reliably encode data on a magnetic disk, without causing deformation of the transducer head, and without causing write induced instabilities. Deformation may occur when a transducer head is overheated due to large write current and/or write current boost amounts at high ambient temperatures. Write induced instabilities occur when~~

~~magnetic domains in the transducer head are pinned by high write current and/or write current boost amounts, causing the read element to become insensitive to data. In general, the write current and write current boost must be sufficiently strong to encode data to the magnetic storage disk such that the data can later be reliably retrieved.~~

- 5     ~~Deformation of the transducer head and write induced instabilities may be detected by monitoring a position error signal and/or a mean square error associated with the transducer head. A sudden change in the position error signal indicates that the transducer head has deformed, and in particular that the pole tip has protruded, due to heating from excessive write current and/or write current boost, and/or that the transducer~~
- 10   ~~head is experiencing write induced instabilities. Similarly, a sudden change in the mean square error of data written with the transducer head indicates a deformation of that transducer head due to heating from excessive write current and/or write current boost. Instabilities can be detected by determining whether an error is indicated while attempting to read servo sector address data.~~

- 15             ~~In accordance with an embodiment of the present invention, a disk drive storage device having a temperature sensor is provided. The temperature sensor may be a discrete component located within or on the disk drive, or may be provided as an additional function of some other component located within or on the disk drive. For example, the temperature sensor may be provided as part of the read/write channel or the~~
- 20   ~~preamplifier of the disk drive. Using the temperature sensor, the ambient temperature of the disk drive is determined. The amount of write current and write current boost for a particular zone of the storage disk addressed by the particular transducer head performing a write operation is obtained from a table of write currents and write current boosts~~

maintained in memory. The amount of write current and write current boost actually provided to the transducer head is then determined according to the observed ambient temperature of the disk drive. The temperature compensation of current amounts ensures that pole tip protrusion does not occur, even at elevated ambient temperatures, thereby  
5 avoiding contact between the transducer head and the storage disk. The temperature compensation of current amounts may also ensure that write induced instabilities do not occur in the read head. In addition, the write current and write current boost amounts may be modified to ensure that a sufficient write current and write current boost are available at reduced ambient temperatures. According to still another embodiment of the  
10 present invention, a table of write currents and write current boosts may be maintained to provide an appropriate current to a transducer head for a given temperature range. According to an embodiment of the present invention, write current and write current boost may be optimized for each transducer head included in a disk drive.

Additional advantages of the present invention will become readily apparent from  
15 the following discussion, particularly when taken together with the accompanying drawings.

## BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a ~~diagrammatic representation of a top view of a conventional computer~~  
20 disk drive, with the cover removed;

Fig. 2 is a perspective view diagrammatic representation of a transducer that  
includes an air bearing slider and incorporating a transducer head;

Fig. 3 depicts a cross section of ~~thea transducer head that includes~~having integrated read and write ~~elements~~heads;

Fig. 4 is a plan view of the ~~transducer head of Fig. 3;~~

Fig. 5A ~~shows the depicts the relationship between a~~transducer head ~~flying over~~ and the surface of a magnetic disk ~~at during normal temperature~~operation;

Fig. 5B ~~shows the depicts the relationship between a~~transducer head ~~flying over~~ and the surface of a magnetic disk at elevated temperatures in accordance with the prior art;

Fig. 5C ~~shows depicts the relationship between a~~transducer head ~~flying over and~~ the surface of a magnetic disk at elevated temperatures in accordance with an embodiment of the present invention;

Fig. 6 is a flow chart ~~of depicting the determining the ation of a~~write current ~~based on and a write current boost in view of the observed bit error rate in accordance with an embodiment of the present invention;~~

Fig. 7 is a flow chart ~~of depicting the determining the ation of a~~write current ~~based on servo information and and a write current boost in view of various types of position errors in accordance with an embodiment of the present invention; and~~

Fig. 8 is a flow chart ~~of determining and updating the write current depicting the operation of a disk drive in accordance with an embodiment of the present invention.~~

## DETAILED DESCRIPTION

Fig. 1 illustrates a ~~typical disk drive, with the top cover removed. The disk drive, generally identified by reference number 100 that,~~ includes a base 104 and a magnetic

disk (or disks) 108 (only one of which is shown in Fig. 1). The magnetic disks 108 are interconnected to the base 104 by a spindle motor (not shown) mounted on or beneath the hub 112, such that the disks 108 can be rotated relative to the base 104. An actuator arm assemblies 116 (only one of which is shown in Fig. 1) are interconnected to the base 104 by a bearing 120 and suspends. The actuator arm assemblies 116 include a transducer heads 124 (only one of which is illustrated in Fig. 1) at a first end, to address each of the surfaces of the magnetic disks 108. A voice coil motor actuator 128, such as a voice coil motor, pivots the actuator arm assemblies 116 about the bearing 120 to radially position the transducer heads 124 with respect to the magnetic disks 108. The voice coil motor actuator 128 is operated by a controller 132 that is in turn operatively connected to a host computer (not shown). By changing the radial position of the transducer heads 124 with respect to the magnetic disks 108, the transducer 124 heads can access different data tracks or cylinders 136 on the magnetic disks 108. A read/write channel 140 processes data signals written to or read from the disks 108, and a preamplifier 144 provides write current signals to the transducer heads 124. In addition, the disk drive 100 may include a temperature sensor 148, located within a cavity 152 that encloses the disk 108 and the actuator arm assembly 116 or on the disk drive 100.

With reference now to Fig. 2, illustrates the a transducer head 124 in more detail. The transducer 124 includes incorporating an integrated read/write head 204 and an air bearing or slider 208 is illustrated. The head 204 reads data from and writes data to the disk 108. The slider In general, the air bearing 208 supports the transducer head 124 on a layer of air created by the spinning of the disk 108 when the disk drive 100 is in operation.

With reference now to Fig. 3, illustrates the an integrated read/write head 204 is shown in cross section, and Fig. 4 illustrates the head 204 in a plan view. The read/write head 204 generally includes an inductive write head or element 304 that writes to the disk 108 and a magnetoresistive read head or element 308 that reads from the disk 108.

5        ~~The write head 304 may be what is known as an inductive head.~~ The write element head 304 generally includes a yoke 310 of magnetically conductive material formed from a write pole 312 and a shared shield 316. A coil 318 of electrically conductive wire is wrapped about a portion of the yoke 310, and ~~is the ends of that coil 318 are~~ connected to a current source (not shown). During a write operation, a write  
10        current is passed through ~~introduced to the coil 318 to in a first direction.~~ The electrical ~~current through the coil 318~~ produces a magnetic field within the yoke 310. At a write gap 320 formed between ~~an end of the write pole 312 and an end of the shared shield 316,~~ the magnetic field spreads out because the magnetic permeability of the write gap 320 is less than that of the yoke 310 itself. The write gap 320 is ~~positioned so that it is in~~  
15        close proximity to the magnetic disk 108, allowing ~~some of the magnetic field to pass through the disk 108 and magnetize a portion of the disk 108 in a particular direction.~~ A  
In a typical disk drive 100 for use in a digital computer, a "1" is encoded on the disk 108 by reversing the direction of the write current, and ~~in which the disk 108 is~~ magnetized from one portion of the track ~~136 to the next.~~ This is done by reversing the  
20        ~~direction of the current in the coil 318.~~ A "0" is encodindicated on the disk 108 by the absence of a change in magnetic polarity. Of course, these conventions ~~can~~ be reversed.

The write current supplied to the ~~conductive wire forming the coil 318~~ is generally ~~in the form~~ a square wave. The write current boost of the write current is generally a write current component having a relatively high amplitude and short duration, and is timed to coincide with the leading edge of the square wave. The write

5 current boost is of particular importance with data written at high frequencies, as the duration of the square pulse of the write current is short, and thus the write current boost makes up a large proportion of the write current. In addition, it is important to control the magnitude of the write current boost, as its relatively high amplitude can significantly heat, and thus expand, the head 304.

10       ~~The write amount of current and write current boost are varied provided during a write operations is, according to the present invention, varied~~ depending on the ambient temperature of the disk drive 100. In particular, because the write current supplied to the coil 318 heats the write pole 312 and the shared shield 316, those elements and the surrounding material of the transducer ~~head-124~~ expand during write operations. When

15 the expansion is large, it is know as pole tip protrusion. Pole tip protrusion increases the likelihood that the write pole 312, the shared shield 316 and other areas of the transducer head-124 will come into contact with the surface of the disk 108, causing errors. In addition, when the ambient temperature of the disk drive 100 is high, the write pole 312 and the shared shield 316, together with the other portions of the ~~read/write head 204~~ are

20 ~~in closer proximity to the surface of the disk 108 because the flying height of the transducer head-124 itself is lower. The lower flying height of the transducer head-124 is due to the a decreased air in the density of the air inside the disk drive 100 at elevated temperatures.~~

The write current boost applied to the coil 318 during write operations also has the effect of heating the write pole 312 and the shared shield 316 and potentially causing pole tip protrusion. Consequently, according to the present invention, both the write current and the write current boost may be adjusted according to temperature. The write current boost is generally applied as a current component having a relatively high amplitude and short duration, and is timed to coincide with the leading edge of the square wave comprising the write current itself. The write current boost is of particular importance in connection with data written at high frequencies, as the duration of the square pulse of the write current is short, and thus the write current boost makes up a larger proportion of the write signal. In addition, it is important to control the magnitude of the write current boost, as its relatively high amplitude can significantly heat, and thus expand, the read/write head 304.

The read element head 308 operates by sensing the magnetic flux transitions encoded in the disk 108 by the write operation. One method of sensing such transitions is with a magnetoresistive head. Such a head is comprised of material that changes its electrical resistance when it is exposed to a magnetic field. Magnetoresistive heads have come into wide use in disk drive systems because they are capable of providing a high output signal. A high signal output is important, because the magnetic fields produced in the disks 108 by the write operation are very small. In addition, the high signal output of the magnetoresistive head allows the data on the disk to be densely packed, in turn allowing the disk drive 100 to have a high storage capacity.

Magnetoresistive heads generally includes the shared shield 316, a strip of magnetoresistive strip material 324 held between two magnetic shields. In the integrated

read/write head 204 illustrated in Fig. 3, the magnetic shields are formed from the shared shield 316 and a read shield 328. The Each end of the strip of magnetoresistive strip material 324 is connected to a conductor (not shown). The conductors are in turn connected to a current source (not shown). Because the electrical resistance of the magnetoresistive strip material 324 varies with the strength and direction of an applied magnetic field, the magnetic flux transitions on the disk 108 result in changes in the voltage drop across the magnetoresistive strip 324. These voltage drop changes in the voltage drop are then converted by the channel 140 into a digital data signal for use by the disk drive controller 132 and in turn the host computer.

The read element head 308 is sensitive to changes in the magnetic domains of associated components, such as the shared shield 316, which can occur during write operations. Such changes can momentarily, or even permanently, render the read element head 308 ineffectual. In particular, the magnetic domains can be pinned in a particular direction, causing the read element head 308 to become insensitive to the magnetic flux transitions on the disk 108. Furthermore, the magnetic domains are even easier to pin at elevated temperature. As a result, the read element 308 is susceptible to write induced instability caused by the write current, especially at elevated temperature.

Preferably, Therefore, it is important that the write current and write current boost supplied to the coil 318 during write operations is not larger higher than necessary to adequately write data to the disk 108, especially at elevated temperature since the read element 308. In addition, it is particularly important to limit the amount of the write current and write current boost supplied to the coil 318 when the ambient temperature of the disk drive 100 is elevated. This is because the read head 308 is particularly

vulnerable to write induced instability insensitivity caused by high write currents and write current boosts when the ambient temperature of the disk drive 100 is elevated. This is believed to be due to the relative ease at which the magnetic domains within the shared shield 316 and other components of the read/write head 204 can be altered at  
5 elevated temperatures.

With reference now to Fig. 4, a typical read/write head 204 is shown in plan view. As described above, the write head 304 generally includes a write pole 312 and a shared shield or pole 316, with a write gap 320 therebetween. The read head 308 generally includes the shared shield 316, a magnetoresistive element 324, and a read shield 328.  
10 Such heads are typically manufactured using thin film layering techniques.

With reference now to Fig. 5A, shows the a transducer head 124 flying over is shown in partial cross section, operatively positioned over the surface of a magnetic disk 108 at normal temperature of the disk drive 100. In particular, Fig. 5A shows the flying height  $h_1$  of the slider 208 flies over the surface of the magnetic disk 108 at a flying  
15 height  $h_1$ ; and Also illustrated in Fig. 5A is the distance  $d_1$  between the tip of the write pole 312 is spaced from and the surface of the magnetic disk 108 by a pole tip distance  $d_1$ . The flying height  $h_1$  is accurately controlled to maintain In general, it is important to accurately maintain the pole tip distance desired fly height  $d_1$  over the surface of the disk 108 so that data is can be reliably written to and retrieved from the magnetic disk  
20 108 by the read/write head 204. This in turn requires that the distance  $h_1$  be accurately controlled.

With reference now to Fig. 5B, shows the transducer 124 flying over the disk 108 at elevated temperature of the disk drive 100 in accordance with the prior art. The slider

208 flies over the disk 108 at a flying height  $h_2$  and the tip of the write pole 312 is spaced  
from the disk 108 by a pole tip distance  $d_2$ . ~~T effects of elevated temperatures on the~~  
~~flying height  $h_2$  and the contour of a conventional read/write head 204 is illustrated.~~ In  
particular, it will be noted that the flying height  $h_2$  is less than decreased as compared to  
5 the flying height  $h_1$ , and the pole tip distance  $d_2$  is less than the pole tip distance  $d_1$ . (see  
Fig. 5A). This is because the ambient temperature inside the disk drive 100 in Fig. 5B is  
higher than in Fig. 5A, and at elevated temperatures decreases the air density in the disk  
drive 100 of air decreases, thereby decreasing the pressure applied to the slider 208 and in  
turn decreasing the flying height  $h_2$ , and the pole tip distance  $d_2$ . Furthermore, the high  
10 write current and the elevated temperature cause ~~In addition, Fig. 5B illustrates a~~  
~~condition in which the transducer head 124 is experiencing pole tip protrusion.~~ In  
particular, it will be noted that various of the elements of the read/write head 204 and at  
least the immediately adjacent area of the slider 208 to have expanded beyond the normal  
contour of the slider 208, represented by the dotted line 504b, thereby creating pole tip  
15 protrusion and in turn further decreasing the pole tip distance  $d_2$ . This condition is know  
as pole tip protrusion, and is typically caused by a combination of elevated ambient  
temperatures within the disk drive 100, and elevated temperatures within the read/write  
head 204 itself due to high write currents and/or write current boosts. The combination  
of a decreased fly height  $h_2$  and pole tip protrusion results in a distance  $d_2$  between the  
20 surfaces of the read/write head 204, such as the tip of the write pole 312, and the surface  
of a magnetic disk 108 that is relatively small. Accordingly, the read/write head 204 is  
more likely to contact the surface of the disk 108, causing positioning errors, and  
potentially damaging the surface of the disk 108. In addition, contact between the

read/write head 204 and the surface of the disk 108 can dislodge particles, potentially causing damage to other portions of the disk 108, or to other components within the disk drive 100.

With reference now to Fig. 5C shows the transducer 124 flying over the disk 108 at elevated temperature of the disk drive 100 in accordance with the present invention. The slider 208 flies over the disk 108 at a flying height  $h_3$  and the tip of the write pole 312 is spaced from the disk 108 by a pole tip distance  $d_3$ . The flying height  $h_3$  is equal to the flying height  $h_2$ , however the pole tip distance  $d_3$  is larger than the pole tip distance  $d_2$ . The elevated temperature decreases the air density in the disk drive 100, thereby decreasing the pressure applied to the slider 208 and in turn decreasing the flying height  $h_3$  and the pole tip distance  $d_3$ , as is conventional. However, the write current is reduced to compensate for the elevated temperature so that the head 204 and the slider 208 remain within the normal contour of the slider 208, represented by the dotted line 504c, thereby avoiding pole tip protrusion and in turn avoiding further decreasing the pole tip distance  $d_3$ .

the relationship between a transducer head 124 and the surface of a magnetic disk 108 at the same elevated temperature as the example in Fig. 5B, in accordance with an embodiment of the present invention is illustrated. Of particular note is the fly height  $h_3$  of the slider 208 above the surface of the disk 108. Specifically, the fly height  $h_3$  is equal to the fly height  $h_2$  shown in the prior art transducer head 124 illustrated in Fig. 5B.

However, it will be noted that the surfaces of the read/write head 204, such as the tip of the write pole 312 in the embodiment illustrated in Fig. 5C, does not extend beyond the plane defining the lower extent of the slider 208, shown by dotted line 504c. This is because, according to the present invention, the amplitude of the write current and of the

write current boost has been decreased to compensate for the elevated ambient temperature of the disk drive 100 in the example of Fig. 5C. Therefore, at the same elevated ambient temperature, the distance  $d_3$  between the tip of the write pole 312 and the surface of the disk 108 in the disk drive 100 in accordance with the present invention is greater than the distance  $d_2$  in connection with the example of Fig. 5B illustrating a transducer head assembly 124 in accordance with the prior art. Accordingly, damage and/or reduced disk drive 100 performance due to contact between the write pole 312 and the surface of the disk 108 is less likely to occur in connection with a disk drive 100 in accordance with the present invention. Moreover, the reduced write current compensates for the elevated temperature. Also, because the present invention provides a reduced write current and write current boost at elevated ambient temperatures, instabilities in the read head 308 are less likely to occur in a disk drive 100 in accordance with the present invention than in the prior art device. Furthermore, as described below, the amount of write current and write current boost are also controlled in accordance with the present invention to reduce or eliminate write induced instabilities in the read element head 308.

The In determining an appropriate write current is determined by considering and write current boost, several factors must be considered. In particular, the write current and write current boost should be large strong enough to produce a magnetic field that capable of provides dueing the desired magnetization of the magnetic disk 108. In particular, the magnetization of the magnetic disk 108 should be sufficiently strong to ensure later allow for the reliable retrieval of data encoded on the disk 108. However, the write current and write current boosts should not be large enough to produce a so great

that the magnetic field produced that at the gap 320 of the write head 304 overwrites data in tracks adjacent to the target track. Furthermore, the write current should not be large enough to cause write induced instability or excessive pole tip protrusion. In general, a nominal write current and write current boost is determined for each transducer head 124 included in a disk drive 100. Alternatively, a nominal write current or write current boost may be determined for less than all of the transducer heads 124 in a disk drive 100 during optimization of the disk drive 100. The optimization process may be performed prior to delivery of the disk drive 100 to the end user. Various combinations of write current and write current boost may be used to write test sequences of data, as will be explained in greater detail below. The levels of write current and write current boost available may be predetermined. For example, a digital to analog converter or converters included as part of the preamplifier 144 of the disk drive 100 may be capable of providing a predetermined number of available output levels.

In addition to determining whether adjacent tracks are overwritten by a selected write current and write current boost combination, according to the present invention, additional aspects of the quality of the write process are considered. For example, the occurrence of pole tip protrusion may be detected by determining whether servo sector position bursts indicate that the transducer head 124 has suddenly changed position relative to the center line of the target track 136. Furthermore, whether instabilities have been created in the transducer head 124 can be assessed by determining whether servo sector address data can be read following the writing of a test sequence of data.

The write current and write current boost determined during the optimization of an individual disk drive 100 may be stored in a table of write currents and write boost

currents accessed by the disk drive 100 when write operations in connection with a particular transducer head 124 are performed. According to an embodiment of the present invention, the nominal write current and write current boost for a transducer head 124 is altered according to an algorithm when the observed ambient temperature of the disk drive 100 falls outside of a range of temperatures about the temperature at which the nominal write current and write boost current is determined. The determination of appropriate algorithms for modifying the write current and write boost current due to changes in temperature will be described in greater detail below. According to another embodiment of the present invention, a write current and a write boost current for each of a plurality of temperature ranges may be stored in a table for each transducer head 124.

With reference now to Fig. 6, is a flow chart of illustrating the determining the ation of an appropriate write current and /or write current boost based on bit error rate at an ambient temperature a desired track width in accordance with an embodiment of the present invention is depicted. The flow chart determines a maximum write current and a maximum write current boost that can be supplied to the head 204 without overwriting adjacent tracks. However, the flow chart does not account for head instability or pole tip protrusion.

Initially, the at step 600, the ambient temperature of the hard-disk drive 100 is measured (step 600). The ambient temperature can be measured by measurement may be taken from a temperature sensor in the cavity 152. For instance, the temperature sensor can be provided as part of another component in the disk drive 100, such as the controller 132, the read/write channel 140, or the preamplifier 144 or the controller 132, or a by a temperature sensor separate component such as the temperature sensor or transducer 148

separately provided as part of the disk drive 100 and located within a cavity 152 (see Fig. 1) enclosing the disks 108 and actuator arm assemblies 116. Alternatively, As an alternative to sensing the ambient temperature within the cavity 152 of the disk drive 100 directly, it should be appreciated that the temperature sensor 148 can be located on an  
5 temperature measurement may be taken from a sensor (e.g., temperature sensor 148) located outside of the cavity enclosing the magnetic disks 108 and the actuator arm assemblies 116. According to still another embodiment of the present invention, the temperature measurement may be taken from a location on a surface of the exterior surface of the disk drive 100.

10        –The write current is set to a minimum level and the write current boost is set to a minimum level i may then be set at a first level, here denoted level 0. The write current boost j may also be set a first level, here also denoted as level 0 (step 604). In accordance with an embodiment of the present invention, the available number of write current and write current boost levels available is dependent on the digital to analog  
15 converter (or converters) included as part of the read/write channel 140 or the preamplifier 144. For example, in accordance with an embodiment of the present invention, 32 different write current levels are available from the preamplifier 144, and 8 different write current boost levels are available in the preamplifier 144, and thus :  
According to this example,  $8 \times 32 = 256$  ( $8 \times 32$ ) different write current and write current  
20 boost combinations are available.

The head 204 writes aAt step 608, a test sequence is written to at least a portion of a center first track 136, and to corresponding portions of each of the two adjacent tracks 136 using the selected write current and write current boost (step 608). During the first

iteration, the selected write current and write current boost are the initial minimum levels.

The head 204 then reads the test sequence from the center track 136, and the quality of the data-written data to the initial track is then assessed by measuring. For example, the bit error rate of the read associated with the test sequence written to the first track 136 is  
5 determined (step 612). An excessive bit error rate will result if the write current and/or write current boost current used to write the data to the two tracks adjacent to the first  
track is too high since writing to the adjacent tracks 136. This is because the strength of the magnetic field produced in the read head 304 is too strong, and the widths of the  
adjacent tracks are therefore too great, causing the sequence of test data in the first track  
10 to be at least partially overwrites the center track 136.

At ~~step 616~~, A determination is made as to whether the measured bit error rate exceeds a specified threshold value (step 616). If the measured bit error rate is within the thresholds specified levels, then a determination is made as to whether the write current  
boost current j is equal to a maximum level value (step 620). If the write current boost j is  
15 not equal to the a maximum level value, then the write current remains at its present level  
and the write current boost j is set equal to j + 1 (i.e. the write current boost is increased  
by one level) (step 624). If the write current boost j is equal to the a maximum  
level value, then the write current i is set equal to i + 1 (i.e. the write current is increased  
by one level), and the write current boost j is set equal to the minimum level an initial  
20 value, here 0 (step 628). After either step 624 or 628 is has been performed, the process  
system returns to step 608, and the head 204 writes the a new test sequence again is  
written to the center a first track 136 and the two adjacent tracks 136 using the increased  
write current or write current boost during the next iteration.

If at step 616 it is determined that the measured bit error rate exceeds the threshold specifications, then a determination is ~~next~~ made as to whether the write current boost is the equal to a minimum level value (here, ~~value 0~~) (step 632). If the write current boost is the equal to a minimum level value, then the write current i is set equal to  $i - 2$  (~~i.e. the write current is decreased~~ reduced by two levels); and the write current boost j is set equal to the a maximum level value (step 636). If the write current boost j is not equal to the a minimum level value, then the write current remains is set equal to i (~~i.e. it is left at its present level value~~) and the write current boost j is set equal to  $j - 2$  (~~i.e. the write current boost is decreased~~ reduced by two levels) (step 640). After completion of either step 636 or 640 is performed, the process system returns to step 608; and the head 204 writes the a test sequence is again written to the center a first track 136 and the two adjacent tracks 136 using the decreased write current or write current boost during the next iteration.

~~It should be noted that the initial level values for the write current i and the write current boost j set at step 604 need not be the minimum level values. For example, the initial level values can may be set at some intermediate levels. This is particularly true when the temperature of the disk drive 100 during such testing is less than a design maximum temperature. Furthermore, different it should be appreciated that the adjustments to the levels can described in connection with Fig. 6 are examples only, and that changes by different amounts may appropriately be used.~~

~~With reference now to Fig. 7, is a flow chart of determining the write current and write current boost at the ambient temperature based on servo information and position error in accordance with the present invention. The flow chart begins where the previous~~

flow chart left off. That is, the maximum write current and write current boost that achieve the specified bit error rate are reduced to avoid head instability and pole tip protrusion.

illustrating the optimization of a hard disk drive 100 based on the avoidance of pole tip protrusion and write induced instabilities is illustrated. Initially, the head 204 writes a test sequence to a track 136 using the selected write current and write current boost (at step 700). During the first iteration, the selected write current and write current boost are the maximum write current and write current boost that achieve the specified bit error rate, as determined in the previous flow chart. a second test sequence is written to a track 136 at the write current i and write current boost j determined during initial testing (e.g., determined using the steps set forth in Fig. 6). The test sequence should be written to multiple data sectors in a relatively long segment of the track 136, to produce heating of the transducer head 124, such as though may occur during the writing of large amounts of user data.

15        -The head 204 then reads servo sector position data from the track 136 immediately following writing the test sequence to the track 136, and refore, according to one embodiment of the present invention, a test sequence is written to multiple data sectors. At step 704, a determination is made as to whether there is an error in the reading read servo sector position data (step 704). As indicated, immediately following the step of writing the test sequence. If an error in the reading the servo sector position data indicates the head 204 has information is encountered, write induced instability that ies are indicated. This is because write induced instabilities causes the read element head 308 to become insensitive to the servo sector position data data stored on the magnetic

disk 108. ~~I~~ Accordingly, if write induced instability ~~is~~ ~~ies~~ are present, then the gray code that used to encode the servo sector position data information in the servo sector encountered following the data sector to which the test sequence ~~i~~ was written, will be unreadable. ~~Accordingly, if an error reading the servo sector position information is encountered, the write current and/or write current boost should be decreased.~~

If no error arises ~~is indicated~~ in reading the servo sector position data, then a determination is made as to whether there is an abrupt change in the position error signal based on the read servo sector position data has been detected (step 708). ~~A~~ In general, an abrupt change in the position error signal indicates that the transducer head 124 under test has experienced pole tip protrusion that causes an abrupt change in the position of the head 204. ~~Specifically, because pole tip protrusion involves a physical change in the shape of the transducer head 124, the position of the head with respect to the center line of the track 136 will change. Accordingly, the position error signal derived from servo sector position bursts included in the servo sector encountered by the transducer head 124 following the data sector to which the test sequence was written, will indicate a sudden change of position. Because pole tip protrusion is typically the result of heating of the transducer head 124 by a write current or write boost current that is too high for the ambient temperature of the disk drive 100, the detection of pole tip protrusion indicates a need to reduce the amount of write current and/or write current boost.~~

Following the detection of an error reading the servo sector position data at step 704, or a sudden change in the position error signal at step 708, a determination is made as to whether the write current boost is the set at a minimum level value, in the present example level 0 (step 712). If the write current boost is the at a minimum level value,

then the write current  $i$  is decreased by one level set equal to  $i-1$ , and the write current boost is set equal to the a-maximum level value (step 716). If the write current boost is not the minimum level equal to 0, then the write current remains  $i$  is left at its present level value (i.e.,  $i$  is set equal to  $i$ ) and the write current boost is decreased by one level  $j$  is set equal to  $j-1$  (step 720). After step 716 or step 720 is performed, the process system then returns to step 700 and the head 204 writes the test sequence again to the track 136 using the decreased write current or write current boost during the next iteration to determine whether the changes have been sufficient to avoid the indicated problem.

If no error in reading the servo sector position data and no abrupt change in the position error signal is detected, then the values for the write current and the write current boost used during the preceding test sequence (i.e. during the previous iteration of step 700) are validated, and stored in a table as may be used as the nominal write current and write current boost for the measured temperature values stored in the table of write currents and write current boosts (step 724).

With reference now to Fig. 8, is a flow chart of determining and updating the write current in accordance with the present invention. The flow chart begins where the previous flow charts left off. That is, the previous flow charts steps followed to adjust the write current and/or write current boosts applied during a write operation based on the observed temperature of the disk drive 100 are set forth. It should be noted that while the steps set forth in Figs. 6 and 7 are generally performed during optimization of the disk drive 100 prior to delivery to the end user, whereas the following flow chart is the steps illustrated in Fig. 8 are performed during normal operation of the disk drive 100 after delivery to the end user. For instance, the following flow chart can steps set forth in Fig.

~~8~~ may be performed every minute for the first 15 minutes after the disk drive 100 has been powered up, and every five minutes thereafter.

Initially, ~~at step 800~~, the ambient temperature of the disk drive 100 is measured (step 800). Next, the temperature adjusted write current and/or write current boost are is  
5 calculated and stored in a table (step 804). ~~Thereafter, At step 808, the~~ a write operation is performed using the calculated write current and write current boost retrieved from the table (step 808).

~~Although the example illustrated in Fig. 8 assumes that an algorithm is used to adjust the write current and write current boost for a nominal temperature to the observed~~  
10 ~~temperature, such is not necessarily the case. For example, different write current and write current boosts can be stored for a variety of temperature ranges. According to such an embodiment, step 804 involves reading a write current and write current boost from a table.~~

~~The~~ The algorithm used to alter the write current and write current boost based on  
15 ~~observed temperature is, according to one embodiment of the present invention, determined for each model or family of hard disk drives 100. According to still another embodiment, a different algorithm for adjusting the write current and write current boost may be developed for disk drives 100 within a family of drives using transducer heads 124 supplied by each different vendor of transducer heads 124 that might be used in that~~  
20 ~~particular disk drive 100. As a further alternative, in particular where a table of write current and write current boost levels containing entries for different temperature ranges is used, the variations in current levels may be developed for each individual disk drive 100.~~

In general, the determination of an appropriate algorithm for adjusting the write current and write current boost involves testing a disk drive 100 can determine the write current and write current boost for in the same manner as described above in connection with Figs. 6 and 7. However, instead of performing such testing at a single ambient temperature, the testing is performed at a variety of ambient temperatures. In this way, a curve describing the performance of the disk drive 100 at various temperatures and for various write currents and write current boosts can be developed empirically. The algorithm used to alter a write current or write current boost for an individual drive should therefore be an algorithm adapted to follow the curve developed for the representative disk drive 100.

Furthermore, it should be appreciated that different algorithms can ~~may~~ be used calculate the write current and write current boost for different temperature ranges. For instance, a first algorithm can ~~may~~ be used to adjust the write current and write current boost amounts at temperatures greater than a selected temperature, and a ~~a~~. A second algorithm can ~~may~~ then be used to adjust the amount of write current and write current boost at temperatures below the selected temperature.

An a ~~An example of an algorithm for use at high ambient temperatures is~~ is as follows:

\_\_\_\_\_ write current adjustment amount =  $5 - ((\text{measured ambient observed temperature} - 27)/5)$

An algorithm for low ambient temperatures is as follows:

~~The resulting value is the number of digital to analog converter levels by which the write current amount is adjusted. An example of an algorithm used to adjust write current levels below a selected temperature is:~~

$$\text{write current adjustment amount} = \frac{(\text{measured ambient temperature} - 55)}{11}$$

The resulting write current adjustment is the number of digital to analog converter levels by which the write current is adjusted. Again, the resulting value is the number of levels by which the nominal write current amount is adjusted. Similar algorithms can may  
be used for adjusting the in connection with write current boost levels. The algorithm or algorithms can may be implemented in firmware or microcode running on the controller 132, and the tables that store the write current and write current boost at various temperatures can be held in . Memory for storing tables may be separately provided or included as part of some other component, such as the controller 132.

The algorithms can be customized for each model or family of disk drives 100, for disk drives 100 within a family of disk drives 100 that use transducers 124 supplied by a different vendors, or for each individual disk drive 100.

The write current and write current boost can be calculated for each zone on the disk 108, for each head 204 in the disk drive 100, and for multiple ambient temperatures both above and below the normal operating temperatures of the disk drive 100. Likewise, the write current and write current boost can be adjusted during normal operation of the disk drive 100 if the measured ambient temperature falls outside a temperature range for the nominal write current and write current boost.

Pole tip protrusion can be detected by a sudden change in the position error signal, or alternatively, a sudden change in the mean square error of data that is written and read by the head 204.

The foregoing discussion of the invention has been presented for purposes of  
5 illustration and description. Further, the description is not intended to limit the invention  
to the form disclosed herein. Consequently, variations and modifications commensurate  
with the above teachings, within the skill and knowledge of the relevant art, are within  
the scope of the present invention. The embodiments ~~described hereinabove~~ are further  
intended to explain the best mode presently known of practicing the invention and to  
10 enable others skilled in the art to utilize the invention in such or in other embodiments  
and with various modifications required by their particular application or use of the  
invention. It is intended that the appended claims ~~be construed to include the alternative~~  
embodiments to the extent permitted by the prior art.

## ABSTRACT

A disk drive provides temperature compensation for write current. The write current not only provides an acceptable bit error rate for data written to and read from the disk, but also prevents write induced instability in the head. Furthermore, the write  
5 current prevents excessive pole tip protrusion. As a result, the write current ensures that data is reliably stored and retrieved at a given temperature.~~having write current and write current boost amounts that can be altered in response to changes in temperature is provided. According to an embodiment of the present invention, the amount of write current and/or write current boost applied in a disk drive is increased as the temperature~~  
10 ~~of the disk drive decreases, and is decreased as the temperature of the disk drive increases. The amount by which the write current and/or write current boost is varied from a nominal amount is controlled to ensure that data is reliably encoded on the magnetic storage disk, while avoiding the overriding of data in adjacent tracks. In addition, the present invention controls the amount by which the write current and/or~~  
15 ~~write current boost is varied to avoid pole tip protrusion and the creation of write induced instabilities within the transducer head. Accordingly, the present invention provides a disk drive that avoids temporary or permanent data errors caused by overheating the transducer head.~~